Renewable and Sustainable Energy Reviews 16 (2012) 2870–2883

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Jatropha curcas: A potential biofuel plant for sustainable environmental development

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ARTICLE INFO

Article history:
Received 13 May 2011
Received in revised form 1 February 2012
Accepted 4 February 2012
Available online 22 March 2012

Keywords:
Jatropha curcas
Eco-environmental benefits
Phytoremediation
Carbon sequestration

ABSTRACT

Jatropha curcas L. (JCL) has been propagated as unique and potential tropical plant for augmenting renewable energy sources due to its several merits for which it deserves to be considered as sole candidate in the tangible and intangible benefits of ecology and environment. The species has been advocated for extensive plantations on degraded wasteland throughout the world. Our current knowledge of JCL is inadequate to understand their contribution in societal and environmental benefit. Presently, this species has received much attention because of its immense role in bio-diesel production an eco-friendly fuel, bio-degradable, renewable and non-toxic in nature compared to petro-diesel except few carcinogenic compounds found in oil cake. However, complete information on the multiple roles of JCL for eco-environmental benefits is lacking. Recent reports on various roles of JCL such as effective phytoremediator, carbon sequester, degraded land developer, and soil erosion controller have been discussed in this communication. Additionally, some of its contribution for medicinal and deriving as therapeutic uses are also highlighted. JCL related problems are also discussed. Further there is a controversial debate on its application, extension, and risks, which needs to be exploited well for its beneficial role in tropical environment. These issues are dealt herewith to observe its future scope to mitigate energy crisis, environmental management and sustainable productions.

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1364-0321/$ – see front matter
doi:10.1016/j.rser.2012.02.004

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1. Introduction

Jatropha curcas L. (JCL) is a multipurpose small tree or large shrub and is found throughout the tropical region. JCL is a tropical species native to Mexico and Central America, but is widely distributed in wild or semi cultivated stands in Latin America, Africa, India and South-East Asia. In India, Portuguese Navigators introduced it in the 16th century. It occurs in almost all parts of India including Andaman Island and generally grown as live fence. It is well adapted to arid and semi-arid conditions.

JCL is a vigorous, drought and pest-tolerant plant and unpalatable by animals. It is planted in tropical countries principally as a hedge, protecting cropland from the cattle, sheep and goats [1,2]. JCL is a diploid species with $2n = 22$ chromosomes. *Jatropha* genome size (416 Mb) [3] is about equal to rice genome (400 Mb) as well as castor genome (323 Mb). Traditionally, *Jatropha* seed and other plant parts have been used for oil, soap and medicinal compounds [4]. *Jatropha* is popularized as unique candidate among renewable energy sources due its peculiar features like drought tolerance [2], rapid growth, and easy propagation, higher oil content than other oil crops [5], small gestation period, wide range of environmental adaptation, and the optimum plant size and architecture make it as a sole candidate for further consideration [6]. Its cultivation requires simple technology, and comparatively modest capital investment. The seed yield reported for *Jatropha* varies from 0.5 to 12 ton year^{-1} ha^{-1} depending on soil, nutrient and rainfall conditions and the tree has a productive life of over 30 years [1,2]. The seeds contain 30–35% oil that can be converted into good quality biodiesel by transesterification [7]. Despite the toxicity of the JCL seeds, edible varieties exist in Mexico [8], which is not currently being exploited. These are often consumed by the local population after cooking. A comparative analysis of edible and non-edible seed varieties revealed that edible seeds lacked phorbol-esters [9,10]. Although oil is more valuable than meal, the seed meal is potentially a valuable commodity. The ability to use JCL meal as animal feed not only improves the economics of JCL production, but also adds its diversified applications in both fuel and feed.

The true potential of *Jatropha* has, however, not yet been realized but now the conditions for its exploitation have improved considerably in recent years due to the increase of crude oil prices and policy incentives for the exploration of indigenous and renewable fuels. Nevertheless, several agro-technological challenges remain for the exploitation of *Jatropha* as a commercial crop. Although *Jatropha* has been scientifically investigated earlier for useful secondary metabolites, the kind of comprehensive research and development efforts necessary to generate economic viability and the critical information of its growth and yield in the different climatic and edaphic regions have only started recently. Results of such research are trickling in slowly; yet, the high market demand for biodiesel has excited in many organizations for the *Jatropha* plantations, because renewable energy is important for sustainable environmental development [11]. The success of these ventures rests on the continuous inflow of relevant information from research into practice [12]. Based on these interesting properties, potentials and hyped claims, a lot of investors, policy makers and clean development mechanism project developers are interested in JCL to tackle the challenges of energy supply and Green House Gas (GHG) emission reduction [13]. Kumar et al. [14] also raised sustainable issues (societal and economical) for promotion of JCL in Indian scenario.

The aim is to develop alternative energy options in rural areas that will help to promote sustainable livelihoods in this region. In this respect switching from fossil fuels or other GHG emitting sources to renewable sources of energy makes sense to combat with the effects climate changes, to have a quality environment around us. The cost of bio-diesel is the most important aspect of promotion of *Jatropha* for bio-diesel production in the country, being eco-friendly, easy to produce raw material, easy oil extraction and transesterification. This review gives a current knowledge of JCL as multifunctional role for eco-environmental benefits and simultaneous wasteland reclamation, carbon sequestration, biodiesel production, and employment generation.

2. Ecological and environmental benefits

2.1. Potential phytoremediator

Researchers all over the world are searching new plant species suitable to be used in phytoremediation. While selecting a species for phytoremediation several factors are considered into account. The species should be fast growing, high biomass producing, with profuse root system, tolerant to adverse environment condition, non edible and economically beneficial [15,16]. Taking all these factors into consideration, JCL seems suitable for phytoremediation. It is regarded as a potential biofuel crop for future due to its low moisture demands, pure hardiness and stress tolerant ability [17]. It grows fast with little maintenance and can reach a height of 3–8 m [17,18]. It has been identified in India and abroad as the most suitable oil bearing plant and has been recommended for plantation on wasteland as it requires minimal inputs for its establishment [18]. So, phytoremediation of polluted soil with non-edible biodiesel plant like JCL offers an eco-friendly and cost effective method for remediating the polluted soil.

Jamil [19] reported that JCL is capable of extracting heavy metals from fly ash (FA) and the extraction is enhanced many folds

in presence of chemical chelants like EDTA. Recently some other researchers also reported that JCL has the potential for remediation of metalloid and metal contaminated soil system. JCL has been implicated in remediation of soil contaminated by heavy metals (Al, Fe, Cr, Mn, Ar, Zn, Cd and Pb) due to its bioaccumulation potential [20–24]. The other species of Jatropha such as *J. dioica* accumulated Zn (6249 mg kg^{-1}) at concentrations near to the criteria for hyper accumulator plants [25].

Agamuthu [26] proved that JCL with organic amendment has a potential in remediating hydrocarbon contaminated soil. Abhilash et al. [27] suggested that remediation of lindane (pesticide) is also possible by JCL. All these efforts are underway to develop an alternative method in removing oil contaminants/heavy metal contaminants from soil while promoting growth of economically viable plant like JCL whose seed can be used for biodiesel production. Furthermore, eco-toxicological risk assessments and validations are required before the using of JCL biomass and biodiesel, grown on heavy metal contaminated areas, in industrial and domestic sectors [28].

2.2. Soil carbon sequestration

In view of environmental considerations, bio-diesel is considered carbon neutral because all the CO_2 released during consumption had been sequestered from the atmosphere for the growth of plants. As a clean renewable energy, it has zero emission of carbon dioxide, causing almost no environmental pollution [29]. Plantation of energy crop is useful in alleviating the CO_2 level in the atmosphere and emission of CO_2 by burning of biodiesel will always be lower as compared to fossil fuel (petro-diesel) hence causing overall reduction of CO_2 concentration in open atmosphere [30]. Positive results on the reduction of GHG are speculated on facts that the global warming potential of the production and use of *Jatropha* bio-diesel is 23% of the global warming potential of fossil diesel [31]. It has been estimated that *Jatropha* biomass production would sequester 5.50 ton CO_2 ha^{-1} $year^{-1}$ [5] and a substantial proportion of the carbon may enter in the soil because of seed cake mulching. *Jatropha* can help to sequester atmospheric carbon (CO_2) when it is grown on wastelands and in severely degraded ecosystems [32].

A study based on the assessment of the biomass potential of marginal lands in Northern China [33], the reduction of CO_2 emission by using bio-energy is expected to be about 75 million ton of carbon equivalents in 2020, which would account for 4% of the total 1.8 billion ton of carbon equivalent of CO_2 emissions in China. In Coming 2050, the reduction of CO_2 emission due to bio-energy is expected to be 150 million ton of carbon equivalents, accounting for 5% of total CO_2 emission. The carbon sink could be sold in the world carbon trade market, which can reduce the cost of bio-energy production and boost the bio-energy development [34–36]. Some authors have also reported that biodiesel emissions depend on feedstock, engine technology, engine power and engine operating conditions [37–41]. Both the feedstock and the injection system play an important role because they influence the fuel spray and consequently the combustion characteristics [42–48]. Thus, utilization of *Jatropha* biodiesel reduces CO_2 emissions and lowers the carbon footprints [49].

Another special feature of JCL lies in its high level of carbon absorption from the atmosphere and stores it in woody tissues and assists in the building of soil carbon. As such the Jatropha crop may also earn carbon credits, whereas, different soil conditions are not receiving the proper attention in the Life cycle assessment studies of *Jatropha* for carbon sequestration to date [32]. Recently, in this direction, a work has been initiated on Jatropha carbon sequestration potential under different edaphic condition in India by Srivastava [50].

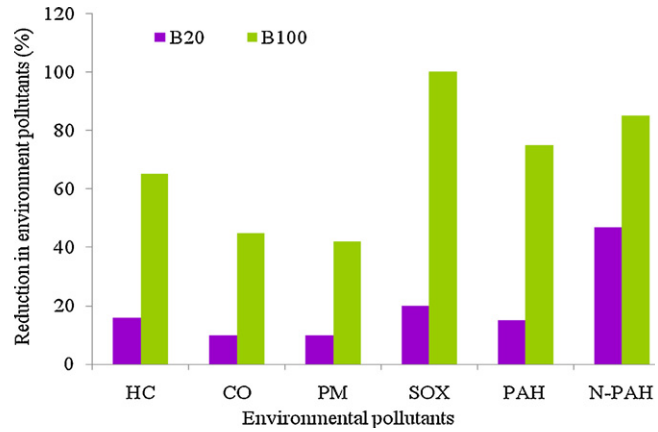

Fig. 1. Using bio-diesel for reduction in environmental pollutants [30] unburned hydrocarbons (HC); carbon monoxide (CO); particle matter (PM); sulphur (SO_x); polycyclic aromatic hydrocarbons (PAH); nitrated polycyclic aromatic hydrocarbons (N-PAH).

2.3. Reduction of environmental pollutants

Besides a considerable reduction in net CO_2 emissions by the replacement of coal with bio-energy, airborne pollutants, such as toxic heavy metals, ozone-forming chemicals, and sulphur dioxide contributing to acid rain, will also be reduced. These atmospheric compounds (CO_2, toxic heavy metals, ozone forming chemicals, SO_2, trace gas air pollutants, etc.) interact with agricultural systems and influence crop performance, either directly by affecting growth and quality or indirectly by altering the plant's ability to cope with other abiotic and biotic stresses [51]. Some researchers have compared the fossil diesel from biodiesel; in which biodiesel generally causes a decrease in unburned HC, carbon monoxide (CO) and particulate (PM) emissions along with an increase in NO_x emissions [52–54]. Many research papers have been reported that the engine operation on biodiesel mixed with diesel gave lower emission than diesel fuel except in case of NO_x. In case of NO_x, there is an increase in 2% NO_x with B20 blending and 10% with B100. Other environmental pollutants were reduced to various degrees by using biodiesel (Fig. 1).

The blending of methanol or ethanol with fossil diesel or biodiesel derived from JCL has been widely investigated as a way to reduce smoke and NO_x [55–58].

2.4. Soil erosion control

Global agro-ecological zoning estimated some 16% of total global land area to be under risk of soil erosion [59]. The percentage of areas under potential erosion risk varies from Europe (19%) to North Africa and the Near East (10%) [59], so, mitigation of soil erosion with using JCL plantations is necessary for sustainability of land. JCL develops a deep taproot and initially four shallow lateral roots [60]. The taproot may stabilize the soil against landslides while the shallow roots are alleged to prevent and control soil erosion caused by wind or water, but this potential has not been investigated scientifically [5]. JCL shows high initial establishment success and survival [61]. Living fences can be established very quickly by planting cutting (vegetative propagation) directly in the field, while taproot is absent in cutting propagated JCL, which makes the plants more susceptible to uprooting by wind. Recently, Reubens [60] demonstrated that the lateral roots of *J. curcas* could decrease soil erodibility through additional soil cohesion, whereas its taproot and sinkers may facilitate exploitation of subsurface soil moisture and thus able to increase vegetative cover, even in very dry environments.

Besides biodiesel production *Jatropha* can also be planted to reduce soil erosion and to stabilize bunds [60]. Plantations established with JCL in different countries had varying objectives: (i) soil erosion control with hedges and combined oil production (biodiesel) in Mali [62]; (ii) reforestation in arid areas for soil erosion control in Cape Verde [63]; (iii) in Madagascar, it is used as a support plant for vanilla; (iv) biodiesel production in marginal areas of India; (v) as energy plantation for the production of methyl esters in Nicaragua. Wind erosion and sand dunes could also be stabilized greatly by the ecosystem reconstruction of degraded land, particularly in arid dry regions.

3. Utilizing marginal land by *Jatropha* agro-forestry

Marginal lands can be managed for the production of renewable energy source as their soil quality and impoverished fertility would not be able to sustain field crops and their rehabilitation particularly in dry land degraded ecosystems could be possible through *Jatropha* plantations. Ogunwole [64] worked on the impact of *Jatropha* cultivation with or without soil amendments on the structural stability, carbon and nitrogen content of a degraded entisol under rehabilitation in western India. JCL plant sheds its leaves and provides plentiful organic matter around the root-zone of the plants and increases the microbial activity including earthworms, which improves the fertility of the soil, which is an indication of ecological improvement of site. The plant itself is believed to reclaim wasteland [1,2]. However, no information is available to date on nutrient cycles and the impact on soil biological activities. The growing concern on these issues must be validated by focused research. Using JCL on barren lands facilitates the secondary succession of native species to enrich the local biodiversity.

Much of the interest in JCL has arisen due to its ability to grow on 'marginal land', and therefore do not compete with the arable land use for food crops. Current estimates suggest that there are now 2.5 million ha of land under JCL planted in India and China alone, with plans for an additional 93078.7 ha by 2010 [65]. Indian Railways uses 2 million kl diesel per year. Indian government made a target to use biodiesel blending at 5% level in the regular diesel supply by 2005–2007 but it could not be possible due to lack of sufficient biodiesel productions. Although, it has been planted along the both sides of the railway tracts covering an area of 2500 km. Also the several state governments have initiated subsidy to the farmers to cultivate *Jatropha* on community wastelands available in villages. About 63.85 million ha, or approximately 20.17% of the total amount of geographical land in India is classified as degraded land or wasteland [66], which urgently require revegetation to prevent further degradation. *Jatropha* plantations for supply of bio-diesel (possibly with additional intangible benefit from C sequestration in soils and standing biomass) could play an important role in the restoration of these lands. Some area may be targeted for the JCL suitability such as degraded and eroded soil, moderately sodic and saline, community wastelands, mine spoils, ravines, rainfed lands (low rainfall zone/rain shadow area), water scarcity areas, replacing uneconomical crops, hedge plantation, railway track, roadsides, riverside, Jhum fallows in hilly areas, to stabilize bunds, erosion prone watershed area, fly ash pond, heavy metal polluted area, etc.

Marginal land utilization has great prospects of augmenting bio-energy resources in the world, with co-benefits, such as carbon sequestration, water/soil conservation and wind erosion protection. Marginal land is defined as the land possessing fragile eco-environment and is unsuitable for agriculture [67,68]. Bio-energy plant species for marginal lands should have some characteristics such as the properties of low water consumption, drought tolerant, salinity and sodicity-resistant, high net productivity, and energy value, and thus has immense potential for being widely planted and for utilization as energy crops. Concomitant eco-environmental benefits can be achieved by using marginal lands for planting bio-energy shrubs instead of abandoned pasture with very low palatable value. The function of soil/water conservation could result primarily from the protection of soil surface and from the improvement of soil structure through root penetration and the addition of organic matter by decomposing leaves, roots, and wood [29,69,70].

Table 1
Various medicinal uses of *Jatropha curcas* [17,72,82,170,171].

S. no.	Usable plant parts	Diseases curing
1	Seeds	To treat gout, arthritis and jaundice, wound-healing, fractures, burns, purge
2	Seed oil	Eczema, skin diseases, soothe rheumatic pain, purgative action
3	Stem	Toothache, gum inflammation, gum bleeding, pyorrhoea
4	Stem bark	Infectious diseases, including sexually transmitted diseases
5	Plant sap	Dermatomucosal diseases
6	Water extract of branches	HIV, tumour
7	Plant extract	Wound healing, allergies, burns, cuts and wounds, inflammation, leprosy
8	Leaves and latex	Refractory ulcers, septic gums, styptic in cuts and bruises
9	Latex	Reduced the clotting time of human blood, sore mouth, oral thrush, fish barb wounds, snake-bites, infected sores, treating newborns' umbilical cords, coughs, mouth and throat sores
10	Root powder	In the treatment of inflammation
11	Leaf	Scabies, Eczema, Syphilis, blood cleansing, headache, flu, cough, congestion, evil eye, cleansing house
12	Fruit	Stroke, toothache, numbness after bug sting, to clean mother's and baby blood during the pregnancy

Marginal land can be better used for *Jatropha* agro-forestry with intercropping of seasonal crops to get income during the gestation period of JCL. Some shade loving crops, short duration pulses, vegetables and shade loving aromatic herb can be profitably grown under *Jatropha* plantation for the first two years. Vanilla can also be cultivated under it successfully as well as export crops such as coffee and cacao. The plant not only protects crops from livestock grazing, but it also has a phytoprotective action against pests and pathogens providing additional protection to intercropped plants. *Jatropha* agro-forestry can develop rural mechanization, electrification and provide onsite fuel as substitution of diesel at village level for pumping water, old tractors, wheat flour mills and other mills.

4. Medicinal values

The genus name *Jatropha* derives from the Greek giatros (doctor) and trophe (food) which implies medicinal uses. According to Correll and Correll [71], curcas is the common name for physic nut in Malababar, India. Medicinal properties are principally found in the *J. curcas*, *J. multifida*, *J. gossypifolia*, *J. macrorhiza* and *J. cinerea* [72]. JCL contains many medicinal values for human and veterinary purposes and has a vast potential for deriving therapeutical values for usage in various segments. All parts of *Jatropha* (seeds, leaves and bark, fresh or as a decoction) have been used in traditional medicine and for veterinary purposes for a long time [73,74]. Some medicinal uses of JCL are given in Table 1.

A decoction of leaves is used against cough and as an antiseptic after birth. Branches are used as a chewing stick in Nigeria [75]. The sap flowing from the stem is used to arrest bleeding of wounds. Nath and Dutta [76] demonstrated the wound-healing properties of

curcain, a proteolytic enzyme isolated from latex. Latex has antimicrobial properties against *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella pneumonia*, *Streptococcus pyogenus* and *Candida albicans* [77]. The latex itself has been found to be strong inhibitors to watermelon mosaic virus [78]. HIV inhibitor properties have been seen in the genus of *Jatropha* [79–81] showed that extracts of *Jatropha* nut fruits have an abortive effect. The methanol extract of *Jatropha* roots exhibited systemic and significant anti-inflammatory activity in acute carrageenan-induced rat paw edema [82,83], and it was found that a methanol extract of physic nut leaves afforded moderate protection for cultured human lymphoblastoid cells against the cytopathic effects of human immunodeficiency virus. Extract of the leaves showed potent cardiovascular action in guinea pigs and might be a possible source of beta-blocker agent [84]. All parts of the plant are used in traditional medicine and active components are being investigated in scientific trials. Several ingredients appear to have promising applications both in medicine as well as a plant protectant.

5. Major role in bio-diesel production

Recently, some of the review articles provide information and status of *Jatropha* biodiesel program in different countries, e.g., UK [85], China [86,87], India [88,89], Malaysia [90,91]. Sweden [92], Thailand [93], Indonesia [94]. In Indian scenario different types of trees (*Pongamia pinnata*, *Pongamia glabra*, *Azadirachta indica*, *Madhuca indica*, *Calophyllum inophyllum*, *Hevea brasiliensis*, *Simmondsia chinensis*) have been identified as source of biodiesel production but JCL is getting maximum attention in research and development work [95]. Furthermore, the sustainability of JCL for biodiesel production from global hype to local solution is a main goal. Low cost and continuous supply of biodiesel is the main trait for its general acceptance. In the context of growing interest for renewable energy sources, liquid bioenergy production from vegetable oils is proposed as one of the possible options to reduce greenhouse gas (GHG) emissions. Against this back ground bio-diesel production from JCL has become a booming business. The oil produced by this crop can be easily converted to liquid bio-fuel which meets the American and European Standards [96,97].

JCL oil has been considered as a prospective feedstock for biodiesel production, particularly due to the possibility of cultivation in dry and marginal lands. However, for use in automobiles, *Jatropha* oil needs to be converted to biodiesel [98]. The oil content in *Jatropha* seeds is around 30–40% and it is potentially the most valuable end product, with properties such as low acidity, good oxidation stability compared to soybean oil, low viscosity compared to castor oil and better cooling properties compared to palm oil. In addition, the viscosity, free fatty acids and density of the oil and the biodiesel are stable within the period of storage [99]. Fuel properties of *Jatropha* bio-diesel are considered to be as good as petro-diesel (Table 2).

Once the seeds have been pressed to obtain the oil, the remaining seed meal can be used as feed in digesters and gasifiers to produce biogas for cooking or produce gas to operate engines, or can be used as manures. In Brazil, the use of JCL oil is increasing because it is thought to be less toxic than castor bean. However, it has a toxin (curcin) similar to ricin from castor bean that is capable of inhibiting protein synthesis [100] and phorbol esters [101] that are toxic and carcinogenic.

Table 2
Fuel properties of *Jatropha* bio-diesel verses diesel oil [5,89,172].

Parameters	Jatropha bio-diesel	Diesel oil
Specific gravity at 15 °C	0.860–0.933	0.82–0.86
Sulphur	0.13	1.2
Viscosity (cSt)	37.00–54.80 at 30 °C	1.3–4.1 at 38 °C
Pour point (°C)	−3	−33 to −15
Cloud point(°C)	2	−15 to −5
Flash point(°C)	210–240	60–80
Cetane number	38–51	40–55
Heating values (MJ/kg)	37.83–42.05	42

6. Beneficial use of *Jatropha* agro-industrial solid waste

Harvested *Jatropha* dried fruit contains about 35–40% shell and 60–65% seed (by weight). *Jatropha* shells are available after deshelling of the *Jatropha* fruit while *Jatropha* seed husks are available after decortications of *Jatropha* seed for oil extraction. Seed contains about 40–42% husk and 58–60% kernels. After oil extraction seed cake is produced as a by-product [102].

6.1. *Jatropha* fruit hulls as bioactive compost

In the process of *Jatropha* oil extraction, a large amount of hull waste is generated. Dry JCL fruit contains about 37.5% hull and 62.5% seed. One ton of *Jatropha* seed is expected to provide about 350-l oil and 2.40 ton hulls. Therefore, in future, disposal of *Jatropha* hulls will create problem if *Jatropha* is being used at a commercial level for biodiesel production. Because the hulls have low density, it is not of economic interest to transport them over long distances for processing. Finding a low cost, environmentally sustainable, long-term solution for handling *Jatropha* hulls is therefore of critical importance. The composition of *Jatropha* fruit hulls (fleshy mesocarp) consists of about 90% dry matter, 46% carbon, 4.3–4.5% crude protein, 0.70% nitrogen, and C/N 67, available phosphorus 146 ppm, pH 8.1, EC 7.50 dS m^{-1}, soluble protein 0.762 mg g^{-1}, total soluble phenolics 1.831 mg g^{-1} [103]. Fig. 2 shows chemical properties and

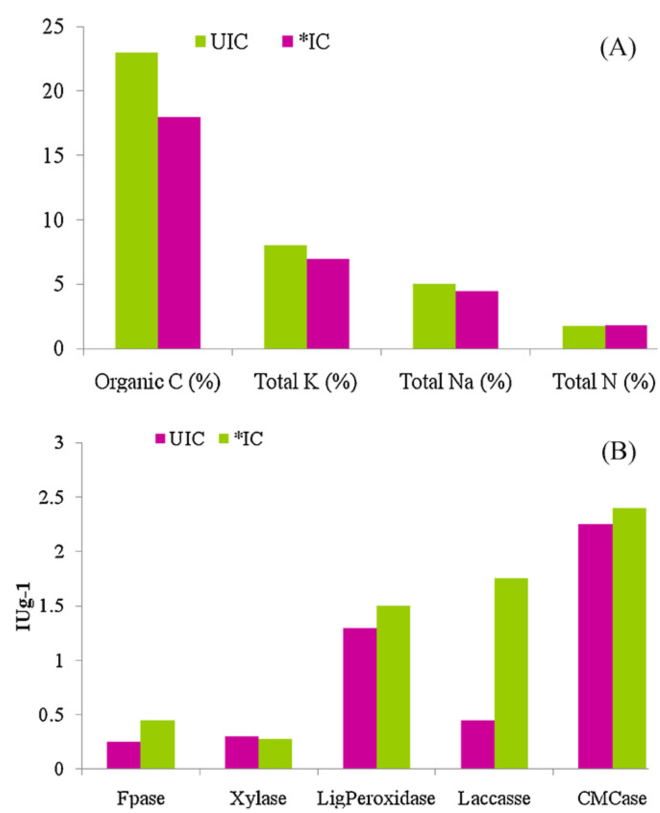

Fig. 2. (A) Chemical properties and (B) extracellular enzymes of *Jatropha curcas* fruit hull/shell biomass in inoculated and uninoculated compost [103]. *Inoculated with mixture of four lignocellulolytic fungi.

extracellular enzymes of JCL fruit hull/shell biomass in inoculated and uninoculated compost.

It has been established that the direct incorporation of hull into soil is considerably inefficient in providing value addition to soil due to its unfavourable physico-chemical characteristics (high pH, EC and phenolic content). Sharma [103] studied that an alternative to this problem is the bioconversion of *Jatropha* hulls using effective lignocellulolytic fungal consortium, which can reduce the phytotoxicity of the degraded material. Inoculation with the fungal consortium resulted in better compost of *Jatropha* hulls within 1 month, but it takes nearly 4 months for complete compost maturation as evident from the results of phytotoxicity test. Such compost can be applied to the acidic soil as a remedial organic manure to maintain soil sustainability of the agro-ecosystem. Likewise, high levels of cellulolytic enzymes observed during bioconversion indicate possible use of fungi for ethanol production from fermentation of hulls. Wever et al. [104] reported high lignin content in Physic nut shells can be used an interesting material for the production of particle boards because lignin is the binding material between the Cellulose and Hemicelluloses fibres.

6.2. *Jatropha seed husk activated carbon as an adsorbent*

Various treatment techniques available for the removal of anions, heavy metals, organics and dyes reduction, ion exchange, evaporation, reverse osmosis and chemical precipitation. Most of these methods suffer from drawbacks like high capital and operational cost and there are problems in disposal of residual metal sludge [105]. Adsorption is comparatively more useful method for the removal of these pollutants. The use of activated carbons to remove inorganic pollutants from water is widely extended due to their high surface area, micro porous character and the chemical nature of their surface [106].

Physico-thermal properties of *Jatropha* fruit shell like bulk density 223.09 kg m^{-3}, moisture content 10.75% wb, volatile matter 71.04% db, ash content 3.97% db, fixed carbon 24.99% db, calorific value 4044 kcal kg^{-1} shows its modest potential to be used in gassifier systems [102]. The *Jatropha* seed contains about 42% husk and 58% kernel. Both husk and shell will be generated in huge quantities as bio-waste in the bio-diesel production which can be used for energy, composting and adsorbent. Therefore, Namasivayam [107] studied the feasibility of using *Jatropha* husk activated carbon for the removal of toxic pollutants from the water and found that *Jatropha* husk activated carbon has significant adsorption capacity and it can be used in decontamination process. We have narrated the contribution of *Jatropha* husk carbon (JHC) in removal of various hazardous compounds (Fig. 3).

6.3. *Jatropha seed cake as manure*

Jatropha seed cake is a by-product of oil extraction. It contains curcin, a highly toxic protein similar to ricin in castor, making it unsuitable for silage. But it is valuable as organic manure which consists of more nutrients in comparison to both chicken and cattle manure [1]. JCL generates approximately 1 ton of seed cake per hectare after extraction of oil. Taking India as a case, it is expected that *Jatropha* will be grown on more than 20 million ha in the next coming years and it is expected to produce about 20 million ton of seed cake per year. This is a significant biomass proportion of organic residue looking for a safe disposal in crop fields to replenish soil fertility; however, at the moment, seed cake is devolved to the crop field for mulching. Jatropha seed cake is useful as a straight soil amendment or a fertilizer [108]. Seed cake can be converted to briquettes for domestic or industrial combustion. One kilogram of briquettes combusts completely in 35 min at 525–780 °C temperature [102,109,110] investigated the process of production of the industrial enzymes such as protease and lipase by solvent tolerant *Pseudomonas aeruginosa* in solid-state fermentation using JCL seed cake as substrate. Oilcakes of JCL consists of various nutrients in different proportions like N (4.91%), P (0.90%), K (1.75%), Ca (0.31%), Mg (0.68%), Zn (55 ppm), Fe (772 ppm), Cu (22 ppm), Mn (85 ppm), B (20 ppm) and S (2433 ppm) [111]. The presence of bio-degradable toxins, mainly phorbol esters, makes the fertilizing cake usable as biopesticide/insecticide and molluscicide [1]. Although the phorbol esters decompose completely within 6 days [112], even then it should be tested in the edible parts if the food crops are grown on *Jatropha* seed cake fertilized land, to ensure their fitness for human consumption. An overview of the experiments which show application of *Jatropha* seed cake as a fertilizer in different trials of crops with positive and negative responses is given in Table 3.

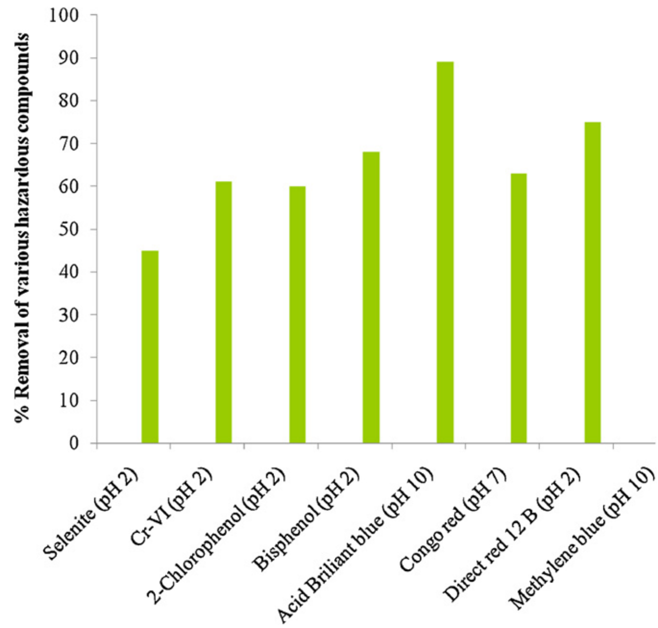

Fig. 3. Contribution of Jatropha husk carbon (JHC) in removal of various hazardous compounds (anions, heavy metals, organics and dyes) [107].

Due to toxicity of the *Jatropha* seeds and oils, adequate attention should be paid on the risk assessment on human health. The fruits contain irritants affecting pickers and manual dehullers [113]. Although JCL has a very long history as medicinal plant, accidental intake of seeds and/or oil can cause severe indigestion problems. For safety reasons, intercropping of edible crops with JCL should only be recommended during the initial 2–3 years period or before JCL starts bearing fruit. The use of the seed cake as fertilizer in edible crop production raises bio-safety questions. Several publications [114,115] suggest that the phorbol esters in the *Jatropha* oil would promote skin tumor. On the other hand Lin [116] and Luo [117] showed anti-tumor effects of the curcin from *Jatropha* oil.

6.4. *Biogas production*

Jatropha seed cake can also be used as feedstock for biogas production through anaerobic digestion before using it as a soil amendment as well. It gives 60% higher biogas compared to cattle dung. In an experiment, *Jatropha* seed cake was utilized as feedstock for biogas production [118,119]. Experiments on use of biogas slurry as suitable manure are still in the early stages. Staubmann [118] obtained 0.446 m^3 of biogas, containing 70% CH_4, per kg of dry seed press cake using pig manure as inoculum. Additionally, the other organic waste products such as *Jatropha* fruit shells, seed husks and pruning waste biomass can be digested to produce biogas (CH_4) [102,120,121]. *Jatropha* produces woody by-products such

Table 3
Applications of *Jatropha* seed cake as a fertilizer in different trials of crops with positive and negative response.

Crops	Scientific name	Dosage	Responses	Country	References
Rice	*Oryza sativa* L.	10.0 ton ha^{-1}	Yield increased 11%	Nepal	[1]
Physic nut	*Jatropha curcas* L.	0.75–3 ton ha^{-1}	Yield increased 13–120%	India	[173]
Physic nut	*Jatropha curcas* L.	20 g plant^{-1}	Higher biomass and yield over NPK application.	India	[174]
Cabbage	*Brassica Oleracea* L.	2.5–1 ton ha^{-1}	Yield increased 40–113% (free from pest and disease, however cutworm infestation occurred with using cow manure)	Zimbabwe	[175]
Tomato	*Lycopersicon esculentum* L.	5.0 ton ha^{-1}	Phytotoxicity reduced germination	–	[176]

as pruning waste biomass and fruits shells which are rather more useful for combustion [122] that will reduce pressure on remaining forests and woodlots. The fact that *Jatropha* seed cake can be used for different purposes makes it an important by-product. Recently experimentation on solid-state fermentation of *Jatropha* seed cake showed that, it could be a good source of low cost production of industrial enzymes [110]. Recycling of wastes as a fertilizer can help to reduce inputs needed for both *Jatropha* cultivation and other agricultural crops or it can produce extra energy in the form of biogas. Digesting the cake and neutralizing the effect of phorbol bringing the effluent back to the field. It is thought to be the best practice at present from an environmental point of view. A number of questions concerning the long-term and cumulative impacts of *Jatropha* seed cake on soils have not been addressed yet. There is need to work on detoxification issues so that the cake becomes viable for the use as animal feed.

7. Other viable use of *Jatropha* oil and by-products

Jatropha oil is also used for some other purposes such as making soap, candles, varnish and lubricant, hydraulic oil, biocides (insecticide, molluscicide, fungicide and nematicide), etc. [122,123]. The most interesting and economically feasible use of the *Jatropha* oil is found in soap production. The glycerine that is a by-product of bio-diesel can also be used to make soap. *Jatropha* oil gives a very good foaming quality in the white soap with positive effects on the skin, partly due to the glycerine content of the soap. *Jatropha* oil is a good fuel for lamps, stoves and poorly running engines (e.g., pumps, mills, generators) [5]. All parts of *Jatropha* are used as raw material for pharmaceutical and cosmetic industries. Another useful by-product is Potassium Sulphate. Besides oil, *Jatropha* seed kernel contains approximately 25–30% protein [2,108]. After oil removal, proteins will remain in the *Jatropha* cake. *Jatropha* seed protein may have similarities with the other well-known oilseed protein such as soy or sunflower protein. In contrast to soy and sunflower, *Jatropha* seed contains toxic compounds such as curcin [116] and phorbol esters [124], which make protein of *Jatropha* unsuitable for food applications. However, the use of *Jatropha* protein in non-food applications is a potential outlet. Possible non food applications of proteins are in the field of adhesives, coatings, chemicals [125–127], fertilizer, such as seed cake fertilizer [2] and amino acid chelated micro-nutrient fertilizer [128]. *Jatropha* leaves are used for sericulture. There will be approximately 30 million ton year^{-1} of *Jatropha* seed to produce oil and that will result 20 million ton year^{-1} of seed press cake as waste. This waste contains approximately 5 million ton year^{-1} of *Jatropha* protein-a high amount that will be highly profitable to process further into a higher value added product [129]. Protein content of *Jatropha* oil cake can be utilized as raw material for plastic and synthetic fibres. *Jatropha* plant can be used as dye, tanning purposes.

8. *Jatropha* based companies and employment

8.1. Jatropha based companies

In Indian scenario, there are many *Jatropha* based companies which have developed processing plants for bio-diesel production and bio-diesel research, such as Reliance Industries, Tata Chemicals, Essar Group, Royal Energy (Mumbai based), SRIPHL (Rajasthan-based) and Vitale Nandan Biopharma Sciences Pvt Ltd. The State Bank of India (SBI) Chennai signs memorandum of understanding (MoU) with D1 Mohan Bio for *Jatropha* cultivation in Tamil Nadu (excluding Nilgiris) by farmers through contract farming. The Chambal Valley in Madhya Pradesh is being looked for a

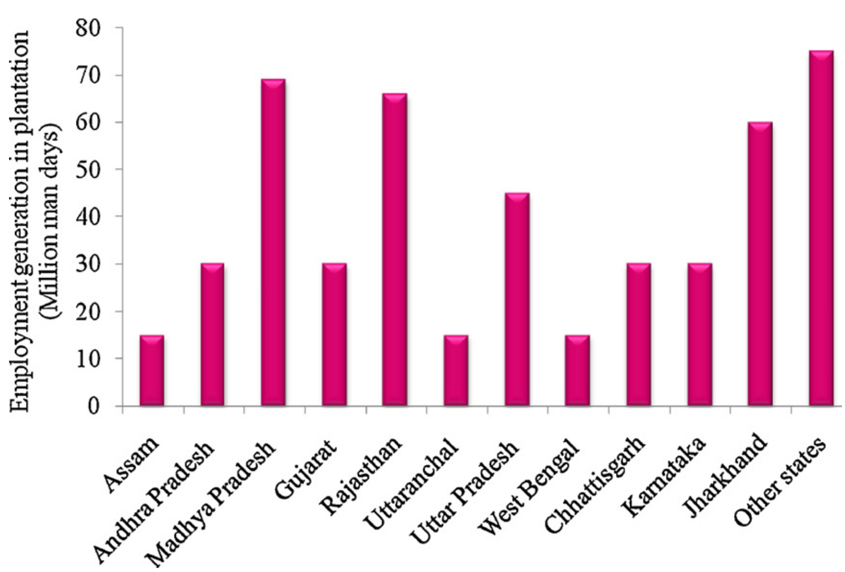

Fig. 4. Employment generation in plantation of JCL in the states of India [88].

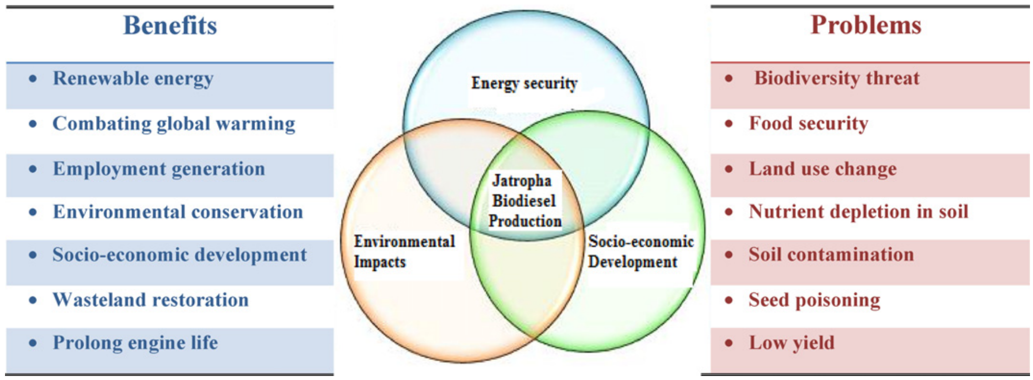

Fig. 5. Potential benefits and problems due to long term Jatropha plantation on commercial scale.

future energy hub, if the Madhya Pradesh government's plan to lease out wasteland to corporate India for cultivation of *Jatropha*. Besides, UK-based D1-BP biofuels has signed a MoU with IL and FS Ecosmart for bio-diesel production in Gujarat. Many other foreign companies are also looking for *Jatropha* cultivation in Gujarat. The biofuel division of Tata chemicals also has plans to extract biofuel from Gujarat and other neighbouring states. The Reliance Life sciences plan to set up a bio-ethanol unit in the Kutch region of Gujarat [130].

In world scenario, three foreign companies have declared so for that they would invest to JCL and set up a factory to produce biodiesel in Sichuan Province [131]. Several international funding agencies such as World Bank, Rockefeller Foundation, Appropriate Technology International, Intermediate Technology development Group – USA, UK and Biomass Users Network are supporting the promotion of *Jatropha* for bio-diesel purpose. Eight Philippine companies have pledged more than $350 million investment towards biofuels production. In England, De-Ord Fuel Company has proposed to use *Jatropha* and waste vegetable oil as feedstock and the company is eager to distribute bus and truck fleets. Australia-based Jatoil Ltd. is requesting the Australian government to allow *Jatropha* cultivation which is banned presently considering it as a noxious weed in the country's (northern region). Jatoil (a green energy company) is focusing on using *Jatropha* oil in biodiesel production. Energy Agriculture Uganda (EAU) Ltd. has 3 shareholders at present.

8.2. Employment

JCL generates net income for 30–35 years from the 4th year of the plantation. Nursery raising by seedling/cutting, *Jatropha* plantation, collection of seeds, de-shelling, oil extraction, etc. provides local jobs to restrict the migration of villagers to cities in search of employment. Electricity from *Jatropha* biodiesel for rural lighting improved the domestic situation and made it easier for the school children to study. National and International organization is working for promotion of tribal communities. Besides, *Jatropha* cultivation and biodiesel production programme also promotes income of tribal communities by several ways, and therefore it may be used for strengthening of economic independency of tribal communities and income through use and sale of *Jatropha* products.

Interest in the cultivation of JCL is coming from both the private and public sectors, and a number of public companies are now involved in JCL cultivation. These companies are generating employment for our society. Biofuel development may offer income-generating opportunities for farmers, as well as promote smallholder participation in biofuel crop production. There would also be employment generation in storage, oil extraction, etc. Employment generation opportunities in plantation of JCL in the states of India are given in Fig. 4 [88].

9. Constraints and problems in *Jatropha* cultivation

It is important to keep in mind that despite of the several advantages that support and promote the use of biofuels, from JCL, its production and end use may have serious environmental impacts which are anticipated loss of biodiversity and food security. One of the major apprehensions regarding biodiesel production is the competition in land availability between energy and food crops to threaten our food security [132]. Loss of naturally occurring biodiversity over the expansion of monoculture is a major environmental threat of a growing concern. Although *Jatropha* is expected to ease fuel shortage and global warming potential, the large-scale cultivation has become a more controversial in many countries including India with a growing awareness of loss of biodiversity and food security (Fig. 5). Other potential concerns arising from the commercial scale cultivation of *Jatropha* may be summarized below.

9.1. Low yield, less oil content and poor economic returns

Despite of the several merits narrated for biodiesel production from JCL, some of the ground level facts were ascertained during the five years in the New Millennium Indian Technology Leadership Initiative (NMITLI) project of Council of Scientific and Industrial Research (CSIR), India and Department of Biotechnology (DBT) project, government of India. Their findings indicate a low genetic diversity among the material collected from different geographical regions of India. Soil and climate of Uttar Pradesh, Uttranchal and north east states of India have not been found suitable for the cultivation of *Jatropha* as an economically viable venture. Conversely, the states like Rajasthan, Gujarat and Andhra Pradesh appear to be more suitable for its optimum production. Many trials have shown the exaggerated yield extrapolated to per hectare area on the basis of per plant fruit or seed yield obtained with a few experimental plants. This infact provides misleading information for its widespread extension. As nearly 50% plants in 1 ha area dose not bear fruit and seed, so in a yearly cycle we get yield from 50% of the population from a unit area. This situation is further compounded by production of kernel less seeds or seeds with rudimentary kernel which adversely affect on oil percent of the bulk lot obtained from unit area in which commercial oil percent is generally extracted not more than 20–22%. Sometimes high vegetative growth also reduces the seed production due to the significant amount of photosynthetic production translocated to the vegetative parts. Asynchronous maturity of fruits is a major constraint in seed harvesting as ripening of fruits continues

throughout the year in successive phases. Generally the winter crop bears good fruits and seeds and the summer or rainy crop produce mostly false seeds (under developed embryo). Flowers of *Jatropha* are not much attractive to the pollinators (mainly insects) and therefore, pollination and fertilization processes are also inefficient to develop a mature and potential embryo. Hygroscopic properties of JCL seeds also affect biodiesel production. Kartika et al. [133] studied relationship between equilibrium moisture content (EMC) and free fatty acid (FFA) content. Generally low FFA content (<3%) is desired for alkali catalysed trans-esterification process in biodiesel production, which can be maintained at low water activity ($a_w < 0.8$).

The crop is generally recommended for degraded waste land to avoid the competition with food crops. As all sorts of degraded lands constitute poor soil structure and low fertility levels, it cannot nourish and sustain the plant adequately for optimum production. Fertilizer inputs further ads to additional cost of cultivation without assured production. Under these situations its economic viability appears to be very low commensurate with inputs. Therefore, it cannot be recommended as such for a commercially exploitable proposition of biodiesel production from wastelands in India, unless the above problems are addressed properly to emerge-out with a standardized protocol to ensure the high yield and oil percent.

9.2. Disease incidence

Mosaic virus disease occurrence in *J. curcas* is reported from India. The virus was found to be transmitted by the vector *Bemisia tabaci* Aleyrodidae in a semipersistent manner, but not through sap inoculation and seed (Fig. 6). The disease is endemic to *Jatropha* not transmitted to any other plant [134,135]. The insect predator *Scutellera perplexa* completed its life cycle exclusively on *J. curcas* and caused severe damage to developing fruit by sap sucking, consequently deals with premature fruit destruction, significant reduction in fruit and seed size and yield [136].

9.3. Impacts of nutrient removal from soils (and subsequent replenishment)

Harvesting of *Jatropha* crop produce (fruit and seed) for biomass energy purpose may cause a significant loss through nutrient removals from site. According to an estimate the amount of energy required to replenish the loss of nutrients would be the equivalent of at least 460 l of oil ha^{-1} [137].

Fig. 6. Field plant showing severe mosaic symptoms.

9.4. Loss of biodiversity

Jatropha energy plantations, in the blanks of natural ecosystems or degraded forest lands can affect both the habitat and food sources of wildlife and other biota. Their expansion in forest area and other natural ecosystems will reduce many preferred habitats and mating areas of some wild life animals such as mammals and birds. *Jatropha* monoculture plantations may reduce the diversity of fast-growing trees vegetation and consequently the loss of habitats for many wildlife species. These *Jatropha* monocultures could be less stable than climax communities in the forest ecosystems and may need more inputs of energy in the form of insecticides, pesticides, fertilizers and other chemicals to maintain productivity.

9.5. Ecosystem impacts

It is also expected that plantation are likely to intensify soil erosion trouble. Producing energy crops such as *Jatropha* may requires additional agricultural land if the venture becomes relatively more remunerative and marginal cropland that is highly susceptible to soil erosion may be brought under *Jatropha* cultivation. Soil erosion contributes significantly in speeding up water run-off, thus, reducing groundwater recharge; the nutrient-rich run-off can harm the quality of receiving rivers, lakes and other water reservoirs by causing eutropification and water contamination. In the years, it may come to a stage where natural forests and croplands are encroached with the plantation of *Jatropha* crops with devastating implication to safeguard the land use matrix.

9.6. *Jatropha* seed poisoning effects

It has been reported that the *Jatropha* kernel is highly toxic to animals [81]. *Jatropha* seed poisoning causes vomiting, nausea and other symptoms resembling to those are induced by some insecticides [138]. El-Badwi et al. [139] also reported that *Jatropha* seeds were found to be lethal for infant's goats between days 7 and 21 causing to bloody diarrhea, dyspnea, and dehydration.

10. Geographical distribution

JCL has a broader geographical range. It is globally distributed in wild or semi cultivated fields in Latin America, Africa, India and South-East Asia. *Jatropha* is a tropical species native to Mexico and Central America where it grows naturally in the forests of coastal regions, but it is found only in the cultivated form in Africa and Asia. In India, it was introduced by Portuguese Navigators in the 16th century. *Jatropha* grows in almost all parts of India including Andaman Island. JCL is also widely grown in Nicaragua, N.E. Thailand and now being promoted in Brazil, Mali and Nepal. JCL was chosen as one of the main oil plant species, especially for Brazil, Nepal and Zimbabwe [2]. It is well adapted to arid and semi-arid conditions. Edible varieties of JCL are also found in Mexico which are not presently being exploited [140]. JCL is listed as a weed in several countries such as Australia, India, Brazil, Fiji, Honduras, Panama, El Salvador, Puerto Rico and other parts of the Caribbean region.

11. Ecology

Jatropha occurs in seasonally dry areas such as grassland-savanna (cerrado), thorn forest scrub and caatingas vegetation, but are completely lacking from the moist Amazon region [141]. The current distribution of *Jatropha* shows that introduction has been most successful in the tropics. *Jatropha* has wide environmental tolerance; it is found in seasonally dry tropics as well as equatorial regions and is well adapted for cultivation within the vast

areas of marginal land and degraded lands in semiarid and arid tropics [142]. It occurs mainly at lower altitudes (0–500). It grows between 15 and 40 °C temperature and under a broad spectrum of rainfall regimes from 250 to over 1200 mm per annum and is more altered by lower temperatures than by altitude or day length [7,143]. Mtinch [144] reported that *Jatropha* even withstood years without rainfall in Cape Verde. *Jatropha* is not adapted to grow below the shadow of forest understory and is unable to compete potentially with fast-growing rain forest vegetation. *Jatropha* grows almost anywhere except waterlogged lands, even on sandy, saline soils, etc. It can thrive on the poorest stony soil and crevices of rocks [145]. It is suitable for sand dune stabilization and soil conservation arenas. In low rainfall areas and in prolonged rainless periods, the plant sheds its leaves to overcome the problem of drought.

Propagation of *Jatropha* may be carried out by cuttings or seeds. Cuttings are typically prepared with one-year-old terminal branches. The rooting of cuttings reaches 100% after 45 days when pre-treated with indole-3-butyric acid (IBA). In practice, one chooses the healthier cuttings of *Jatropha* plantation for field acclimatization. The benefit of cutting propagation is that it offers the possibility to grow privileged accessions. The cuttings and seedlings of *Jatropha* are grown in nurseries for 2–6 months and thereafter transplanted on the field at the beginning of the wet season. It is a good practice to inoculate cuttings with mycorrhizal fungi when establishing them into nursery. This treatment improves the quality of the plant-fungal symbiosis in the field conditions especially in soil with poor fertility [146]. However, plantations at commercial level are only possible through seed sowing. Before sowing, seeds are soaked for 24 h in water, which germinate in 5–10 days at 27–30 °C in saturated humid condition.

Occurrence of vivipary in *J. curcas* is another important concern related to its natural propagation phenomenon. Fruits are harvested at seed maturity, which occurs 40 days after flowering. If fruit harvesting is delayed by few days, most of the *Jatropha* seeds germinate under high humid conditions, thus reducing seed oil content and the seed yield per unit area [147]. Understanding the physical properties of the *Jatropha* fruit is very necessary for harvesting, drying, cleaning, grading, decorticating, and storing [148,149].

12. Genetic diversity

J. curcas is essentially cross pollinated, which results in a high degree of variation and offers the breeder ample scope to undertake screening and selection of seed sources for the desired traits [150]. Selection is the most important activity in all tree breeding programmes [151]. Since variability is a prerequisite for selection programme, it is necessary to detect and document the amount of variation existing within and between populations. Field testing of the performance of *Jatropha* hybrids is undergoing at various research centers. In *J. curcas* provenances, available in India, only modest levels of genetic variation were observed, while wide variation was found between the Indian and Mexican genotypes [152]. Identification of promising lines among the germplasm collections would entail a concerted study over a period of time, usually 5–10 years. *J. curcas* has significant genetic variability in many characters. The differences among the genotypes were also found when aggregate effect of all characters was tested by Wilk's criterion [153]. There is no association between eco-geographical distribution of genotypes and genetic diversity as genotypes selected under diverse locations. This kind of genetic diversity might be due to differential adoption, selection criteria, selection procedure and environment [154]. This indicated that genetic drift produced greater diversity than the geographic diversity [155,156].

The most important trait contributing maximum genetic diversity on the basis of appearance was seed oil content (33.3%, 12) followed by kernel based oil content (58.33%, 21) as per cent contribution and rank total, respectively. The character contributing maximum diversity can be given more emphasis for the purpose of fixing priority of parents in hybridization program. It is also suggested that for creating variability and developing the best selection, a large number of divergent lines, instead of few should be used in the hybridization.

Genetic diversity in relation to seed yield and oil content in 42 Indian accessions showed modest level of genetic diversity by 400 RAPD (Random Amplification of polymorphic DNA; Genetic fingerprinting technique) as reported by Ginwal [157] and Kaushik [17] and 42% molecular polymorphism and 100 ISSR (inter simple sequence repeat: genetic fingerprinting technique, 33.5% molecular polymorphism) primers [152]. In other tests with 23 selected provenances from 300 collected provenances in India 8–10% AFLP (Amplified fragment length polymorphism: genetic finger printing technique) and 14–16% RAPD polymorphism was found [158]. AFLP analysis of 161 accessions, acquired from different biogeographic regions of India, indicated the low diversity with only six broad spectrum graphs of divergent lines (K.V. Bhatt, personal communication). Single-primer amplification reaction (SPAR) and inter-simple sequence repeats (ISR) based genetic diversity of JCL germplasm has been studied in India and China [159,160]. These studies reported adequate diversity between screened accessions and recommended for genetic improvement of JCL in India and China.

13. Discussion and conclusion

JCL has low nutritional requirements, but the soil pH should not exceed 9 [121] and on very acidic soils JCL might require some Ca and Mg fertilization. JCL is well adapted to marginal soils, but in order to support a high biomass production the crop required desired inputs in terms of nitrogen and phosphorus fertilization [7]. Mycorrhiza assisting with the uptake of phosphorus and microelements were found on the root system [1,2,61]. Mycorrhiza-inoculated JCL showed a 30% increase in both biomass and seed production at 7 months after plantation of 1-year-old saplings [97]. The establishment and good management of *Jatropha* plantations on the degraded land will not only lead to carbon sequestration in soil and standing biomass, it will also reduce soil erosion and help to improve the soil and water quality. Rajaona et al. [161] investigated that pruning affects growth, canopy size and leaf area density. This might be useful to increase seed yield without formation of higher wood density. Pruning of JCL promotes initiation of primary branching and higher productivity. Agrotechnology of JCL has not been standardized; however, some fragmenting information on spacing and pruning treatments have been published recently [161,162], which concluded that pruning of large lateral branches, with shorter main stem, rendered significantly higher growth and biomass in comparison to plant with small laterals and longer main stem. Intercropping plantations serves the dual effects for the biodiversity conservation as well as some income from the unutilized and underutilized degraded lands. As a hedge, *Jatropha* can be used as a living fence, to restrict browsing animals from free grazing of the crops because it is unpalatable to livestock [61,108]. JCL plantation should not be considered yet as a highly profitable cash crop unless the value of by-products and other advantages are duly recognized. Besides, raising of intercrops along with JCL as an oil crop and other potentially high value products such as glycerine and utilization of seed cake make it more attractive venture. If it could be effectively marketed and the adequate value of environmental (carbon sequestration) and socio-economic returns (wasteland reclamation) is added then it becomes a viable prescription model. However, large scale plantation of JCL has not expended much due to poor yield, low monetary returns and growing awareness about the

environmental risks (e.g., loss of biodiversity and water recharge) [163] and social problems (e.g., food security) [164–166]. Recently, some accessions of JCL have been screened out through large scale plantations with higher yield and oil content [162]. In Zimbabwe, the availability and suitability of various land types as well as agro-ecological conditions for the production of JCL was assessed by Jingura et al. [167]. Jingura [168] also discussed the technical interventions at two levels of the value chain that are required to optimize production of JCL as a commercially viable energy crop.

Furthermore, *Jatropha* bio-diesel offers environment-friendly development with economic and ecological advantages that include lowering of pollutant emissions (greenhouse gases) increasing of rural employment, energy security and decreasing the dependency on fossil fuel (imported oil). In this discussion, JCL plays diverse positive role related to environment, as it is claimed to produce bio-diesel and enhance economic development while reclaiming marginal and degraded lands in (semi-)arid regions [1], without competing with food production or depleting natural carbon stocks and ecosystem services. Multiple benefits of JCL can be achieved by future critical research efforts to provide new impetus for local and regional sustainable development [169].

To summarize, the *Jatropha* development programs, it is realized that many positive ecological, environmental, energy and economic aspects support its further extension which are attached with the commercial exploitation of this plants. We hope that the *Jatropha* system will find a wider acceptance in the world if carbon credits are applied to the grower and oil producer. There are many benefits and potential of JCL such as reliable biodiesel supply, reduction of GHG emissions, cost effectiveness, tribal community development, biogas production, medicinal value, initiating the biological activity in inert soil, supporter for vanilla plant, employment generation, wastelands utilization, carbon sequester, soil erosion controller, potential phytoremediator, use of seed cake as organic manure, 100% whole fruit utilization for energy direct and indirect applications in environment and agricultural sector (fruit shell for domestic and industrial combustion after briquetting, seed husk and seed cake for biogas production, seed oil for biodiesel, seed cake in compost).

14. Recommendations and future perspectives

In view of the aforesaid discussion to support its extension particularly on degraded wastelands it becomes more important to develop new varieties and hybrids which could produce the high seed yield (5–10 ton ha^{-1}), and a good percentage of oil content (35–40%) at the minimum amount of input. New biotechnological approaches should be applied for making desirable characteristics in genetically modified JCL crop. Development of new improved varieties of JCL which lack curcin and phorbol-esters should be a desirable target. This would allow the seed meal to be used as animal feed and other purposes and eliminates risks to human health associated with the *Jatropha* toxins. The recognition of a molecular marker related with the absence of curcin and phorbol-esters would facilitate breeding programmes accordingly. Additionally using GIS data one can know the availability of land, type and quality that may be used for *Jatropha* cultivation. We must ascertain the availability of land and or strategies required to ensure meaningful plantations with climate based optimum yield having sufficient oil percent without compromising other vital forms of land use. Furthermore, nations that are subsidising fossil fuels may need to reconsider such subsidies and tax in favour of biodiesel production. The money from taxes should be used to the development of *Jatropha* biodiesel sector. Technologies related to value addition of by-product should be used for the promotion of *Jatropha* biodiesel. Integrated agro-technologies should be applied for enhancing *Jatropha* seed yield by using some agronomic practices such as mass multiplication of elite germplasm by tissue culture or macro-propagation, standardization of optimum plant density (spacing between plants), making good plant architecture by pruning, using flower and growth enhancing hormones, to appropriate male: female ratio in the flowers. Integrated nutrient management (fertilizers, VAM, biofertilizers like *Azospyrillum*, *Bacillus*, phosphobacterium, etc., Zn/K mobilizer), using plant growth promoting rhizobacteria (PGPR), using biocontrol agents Viz. *Trichoderma*/*Pseudomonas*, manipulation of flowering by drip irrigation practices, using bee hives for better cross pollination are suggested for a grand success in years ahead.

Acknowledgements

Vimal Chandra Pandey is thankful to University Grants Commission, Government of India, New Delhi for awarding UGC-Dr. D.S. Kothari Post-Doctoral Fellowship. Authors are thankful to the Head, Department of Environmental Sciences, Babasaheb Bhimrao Ambedkar (Central) University for providing facilities. Kripal Singh expresses his thanks to Council of Scientific and Industrial Research, New Delhi for awarding Senior Research Fellowship.

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